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ANALYSIS OF SEASONAL VARIATIONS IN SOIL TEMPERATURE AT A URANIUM TAILINGS DISPOSAL SITE - A COMPARISON WITH THEORETICAL DATA

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ANALYSIS OF SEASONAL VARIATIONS IN SOIL TEMPERATURE AT A URANIUM TAILINGS DISPOSAL SITE - A COMPARISON WITH THEORETICAL DATA

by

M.G. Grenier* and J. Bigu**

ABSTRACT

Soil temperatures in a uranium mine tailings dam were measured at regular intervals up to a depth of 5 m. The study was conducted at a tailings disposal site, 21 km northeast of the town of Elliot Lake, Ontario, between October 1982 and July 1983. The experimental soil temperature profiles were compared to simplified statistical macroclimatic models for estimating soil temperatures. At depths greater than 50 cm the model used approximated experimental temperatures within 1 or 2°C on average over a period of 10 months. In order to implement these models, meteorological variables such as air temperature, rain and snowfall were measured. The influence of snow cover on soil temperature and the advance of the frozen front was studied. The data reported here are part of a program aimed at investigating long-term trends in radon gas emanation from tailings piles and its radiological and environmental impact.

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ANALYSE DE LA VARIATION SAISONNIERE DE LA TEMPERATURE DU SOL DANS UN CIMETIERE DE RESIDUS DE RAFFINERIE D'URANIUM

par

M.G. Grenier* et J. Bigu**

RÉSUMÉ

La température du sol, dans le barrage de résidus d'une mine d'uranium, a été mesurée à intervalles réguliers jusqu'à 5 mètres de profondeur. L'étude s'est effectuée d'octobre 1982 à juillet 1983, dans un cimetière de résidus situé à 21 kilomètres au nord-est de la ville d'Elliot Lake, en Ontario. Les profils de la température du sol ainsi mesurée ont été comparés aux données de modèles macroclimatiques, simplifiés pour évaluer ces températures. À plus de 50 centimètres dans le sol, les températures théoriques utilisées dans le modèle se situaient, en moyenne, à 1 ou à 2 °C des températures réelles, sur une période de 10 mois. Pour mettre ces modèles à l'essai, il a fallu mesurer des variables météorologiques comme la température de l'air et les précipitations de pluie et de neige. Le rôle joué par la couverture neigeuse sur la température du sol et la progression du front de gel a été étudié. Les données que nous signalons ici font partie d'un programme visant à analyser les tendances à longue échéance de la libération de gaz radon des tas de résidus et de ses répercussions radiologiques et environnementales.

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INTRODUCTION

Soil temperatures (TS) are controlled by solar radiation absorption, soil thermal properties and meteorological variables such as snow cover, wind and rainfall. From the reclamation point of view, frost penetration and soil temperature will influence vegetation as well as insect population. Furthermore, the depth of frost and the recession of frozen boundaries in springtime may affect melting water drainage.

The advance and the recession of the frozen boundaries are also of interest to the extent that they affect the transport and emanation of radon gas. The data reported here were obtained during experiments designed to monitor the effect of meteorological variables on radon gas exhalation from a uranium tailings disposal site (1). The temperature profiles observed at various depths for a period of ten months were analyzed and compared to those obtained from available numerical models.

ESTIMATION OF SOIL TEMPERATURES AND FROZEN BOUNDARIES

Several models have been described that approximate soil temperatures from surface meteorological data. One such model was developed by Goodrich (2,3) and adapted by Hayhoe et al. (4). This model consists of solving the heat conduction equation by using a centered-difference formulation and solving by Gaussian elimination. This model is quite sophisticated; it requires a great deal of data manipulating and computer processing time and for this reason was not used here.

A different approach is used by Ouellet (5) to estimate monthly soil temperatures. This method arises from a regression analysis based on anywhere

from 1 to 10 years of soil temperature data originating from forty-one Canadian stations. These data can be analyzed and multiple regression equations may be developed, such as:

$$TS(Z) = b_0(Z) + b_1(Z)X_1 + b_2(Z)X_2 + b_3(Z)X_3 + \ldots + b_8(Z)X_8 \qquad \text{Eq 1}$$

where, TS is the estimated soil temperature (°C) and b_0 to b_8 are regression coefficients listed elsewhere (6). The symbol Z stands for soil depth in cm. X_1, X_2, ... X_8 are the soil temperatures of the previous month, the mean maximum and minimum air temperature, the absolute maximum and minimum air temperature, the number of rainy days, the amount of rainfall and snowfall (mm) for the month of interest, respectively. This method was used to compare with experimentally determined soil temperatures at the tailings site.

The advance of the frozen front was experimentally measured, as well as estimated from a simple differential equation derived from the heat flow by conduction equation (7):

$$C \frac{\delta T}{\delta t} = - \frac{\delta F_Z}{\delta Z} \qquad \text{Eq 2}$$

where, C is the volumetric heat capacity (cal cm^{-3} $°C^{-1}$)

T is the temperature (°C)

Z is the depth (cm)

t is the time (s)

k is the thermal conductivity (cal cm^{-1} s^{-1} $°C^{-1}$)

and F_Z is the heat flux in the Z-direction and is equal to $- k \frac{\delta T}{\delta Z}$. If we assume that the material is isothermal at the freezing point and further that there is no heat flow from underlying thawed material we arrive at the Stephan formulation for the position of the frozen front as a function of time and surface temperature (7):

$$X_f = \sqrt{\frac{2kf}{L} (T_f - T_s)t} \qquad \text{Eq 3}$$

where, X_f is the position of the frozen front (cm)

k_f is the thermal conductivity of the frozen material (cal cm^{-1} s^{-1} $°C^{-1}$)

L is the ice volumetric latent heat of fusion (cal cm^{-3})

T_f is the freezing point of water (°C)

T_s is the surface air temperature (°C)

t is the time (s)

In the above Equation, L is obtained by (7):

$$L = 79.77\ Sn \qquad \text{Eq 4}$$

where, S and n are the degree of saturation and porosity of the soil which were measured experimentally to be .172 and .538, respectively (1). This yields a value of 7.38 cal cm^{-3} for L. The thermal conductivity of the frozen material was calculated from Kersten's expression used by Hayhoe (4):

$$k_f = 3.415 \times 10^{-6} \times 10^{1.38\rho} + 2.9 \times 10^{-3} W \times 10^{.5\rho} \qquad \text{Eq 5}$$

where, ρ is the bulk density measured to be 1.34 g cm^{-3} (1) and W is the gravimetric water content measured to be .0724 (1). This implies a value of k_f of about 1.23×10^{-3} cal cm^{-1} s^{-1} $°C^{-1}$ and hence, from Equations 3, 4 and 5:

$$X_f = \sqrt{.00153\ t} \qquad \text{Eq 6}$$

if we assume an average surface temperature of approximately -4.6°C between November 1982 and January 1983. This is a crude estimation of the advance of the frozen front but will be seen to yield a fairly good first approximation.

DESCRIPTION OF TAILINGS SITE AND APPARATUS

The study site is an inactive tailings pond approximately 21 km northeast of the town of Elliot Lake, Ontario. Soil temperature measurements were made on a dam situated on the eastern side of the pond. At the site of measurement the tailings material could be described as loose to compact,

light brown to grey, fine sand and some silt. The clay colour changes from light brown to grey at approximately 100 cm, accompanied by a greater compactness from 100 cm to 130 cm. At the experimental site and in the immediate surroundings the surface was bare, resulting in a very loose surface layer, approximately 15 to 20 cm deep.

Figure 1 shows a cross-section of the tailings dam and the configuration in which thermocouples were installed for temperature measurements. Nine thermocouples spanned a depth between 8 cm and 498 cm in increments of 60 cm. These copper-constantan thermocouples were designed in-house to withstand the highly corrosive and wet environment in which they were to be used. Holes in which the thermocouples were installed were 2.5 cm in diameter and were easily 'punched' to a depth of up to 5 m using a soil sampler hand auger. After the thermocouples were installed and the holes carefully backfilled to within 50 cm from the surface, bentonite was laid around the thermocouple wire so as not to disturb radon gas concentration measurements being made nearby (1). A more complete summary of thermocouple design and installation is given elsewhere (8). The thermocouples were read to within .5 °C using a Fluke (Model 2166A) Digital Thermometer. Soil temperature measurements at the site were taken weekly from the beginning of October 1982 to the end of July 1983.

RESULTS AND DISCUSSION

Figure 2 shows the soil temperature as a function of depth for several times of the year as measured at the tailings dam. From this figure it can be seen that at a depth of 5 m the yearly temperature amplitude (range between the yearly maximum and minimum temperature) is approximately 6°C, whereas for depths of less than .1 m the temperature may vary by 20°C. It is possible for the shallow depth temperature amplitude to be much greater

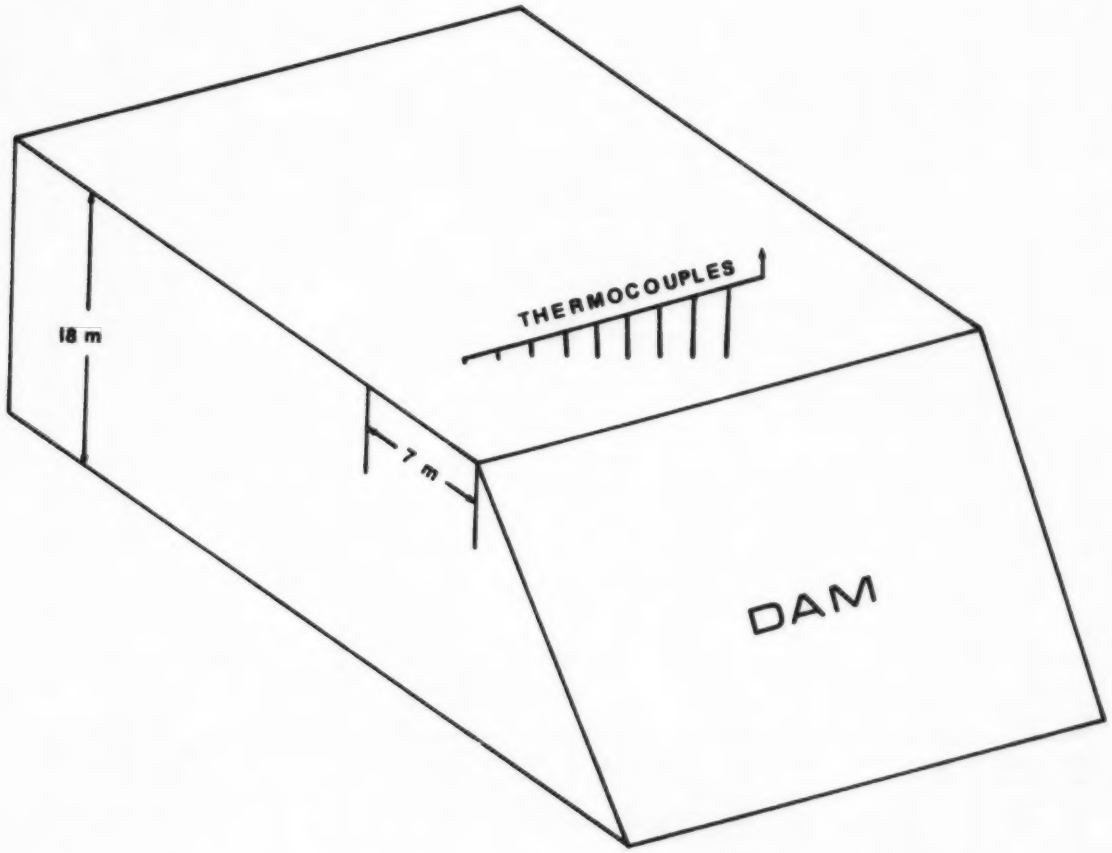

Fig. 1 - Cross-section of the dam tested, showing the emplacement and configuration in which thermocouples were installed.

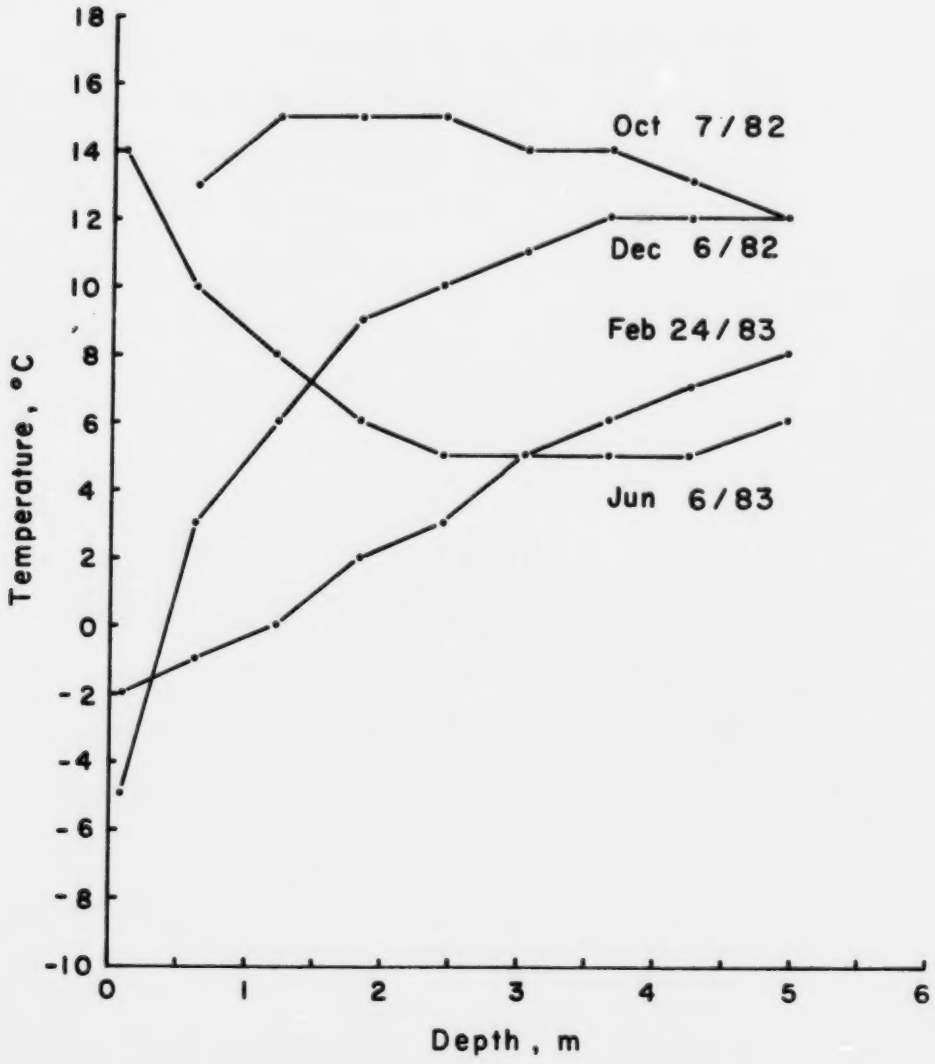

Fig. 2 - Temperature profiles as a function of depth, showing the effect of seasonal surface temperatures.

than 20°C depending on soil characteristics, snow cover or lack thereof, as well as surface temperature minima and maxima. During the course of these experiments temperatures were observed to vary by more than 40°C at a depth of 8 cm. At some depth ($Z > 6$ m) variations in soil temperature are non-existent (Ouellet (5) quotes that on average the depth at which there is no temperature variation is about 11.6 m. This is based on 130 Canadian station-years). From Fig. 2 it is possible to estimate that this constant temperature would be around 9°C.

Figure 3 shows experimental temperature profiles at various depths. In the 8 cm profile the temperature varies by 44°C. At this depth the soil temperature fluctuates by as much as 15°C from one week to the next. These large fluctuations are caused by similar variations in surface temperature and the high thermal diffusivity of the first few cm of loose sandy tailings material. The only extended portion of the 8 cm profile that does not fluctuate by more than 2°C is a period of approximately 40 days in February and March 1983. At all times in this period the snow cover was at least 30 cm thick. Prior to this, no permanent snow cover existed and heavy rains in March caused a complete melting of the snow cover. The importance of snow cover and its effect on TS are well documented. Hayhoe et al. (4) reported data that show widely fluctuating TS values at a depth of 20 cm on a site that was purposely kept clear of snow. Under these conditions TS varied by as much as 7°C from day to day. In an adjacent plot where the natural snow cover was not disturbed, TS at 20 cm never varied by more than 1°C from day to day. Figure 3 also shows TS curves at depths of 61 and 122 cm. It can be seen that there are much less fluctuations in TS as depth increases. Along with a TS amplitude decrease, Fig. 3 also shows a time lag of the minimum yearly temperature. This time lag is plotted for various depths in Fig. 4.

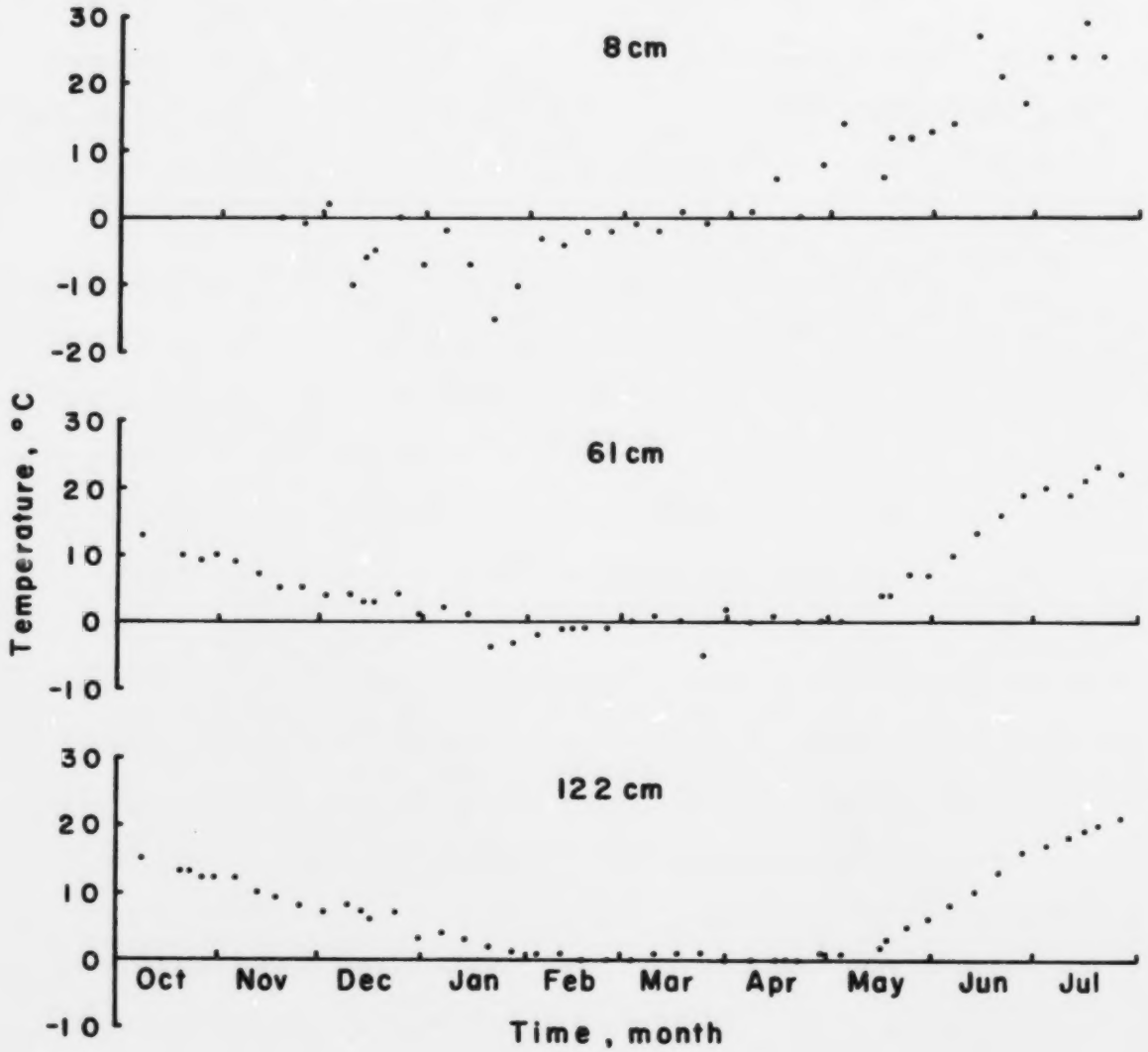

Fig. 3 - Experimental soil temperatures at 8, 61 and 122 cm as a function of time between October 1982 and July 1983.

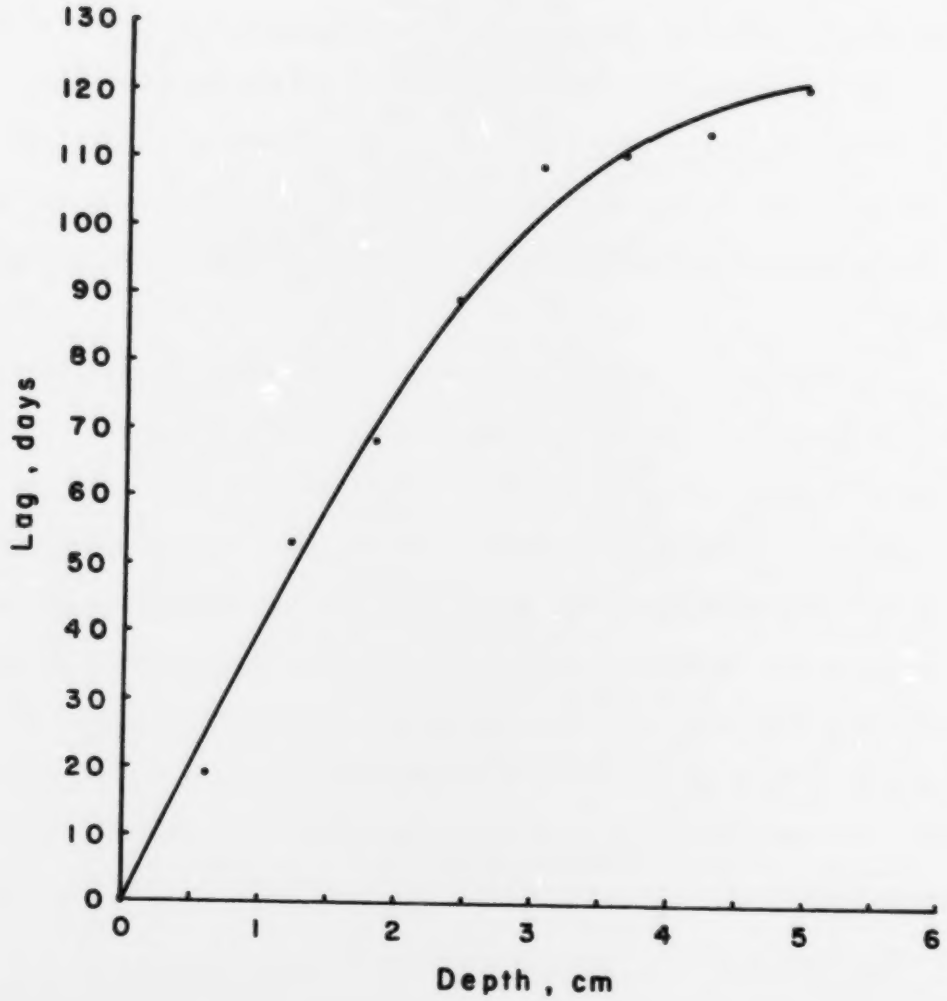

Fig. 4 - Experimental data showing time lag between yearly minimum surface temperature and yearly minimum soil temperatures as a function of depth.

Figure 4 shows that there can be as much as a three month difference between the time when surface temperature reaches a yearly minimum value and that when the same minimum occurs at 5 m. This phenomenon is ascribed to soil thermal diffusivity and can be estimated by equations describing the propagation of sinusoidal temperature variations on the surface of homogeneous soils. Ouellet (5) quotes statistical results for Canada that show a lag of approximately 60 days between the 1 cm and 100 cm depths. In the case of interest here the lag was approximately 45 days between the same two depths. This lower value is probably a result of lack of snow cover and different soil properties.

Figure 5 shows experimental monthly TS averages interpolated from thermocouples read at the tailings dam as well as monthly TS profiles as obtained by Ouellet's short statistical regression analysis. The input variables needed for Ouellet's analysis are the mean maximum and minimum monthly air temperatures as well as the absolute maximum and minimum monthly air temperatures. These were calculated from data obtained on a daily basis from the municipal airport. Other variables needed are the number of rainy days and the amount of rainfall and snowfall per month in millimetres. The first two variables were measured by a rain gauge electronically coupled to an automatic data logger (1) while snowfall was estimated from weekly observations at the experimental site.

Very good agreement exists between the experimental and theoretical TS profiles. The largest discrepancies occur at shallow depths. This is mainly due to the difference in soil thermal properties near the surface. The model is based on data gathered in soils under short grass cover, whereas in the case reported here the surface layer is bare and made up of coarse cyclone tailings.

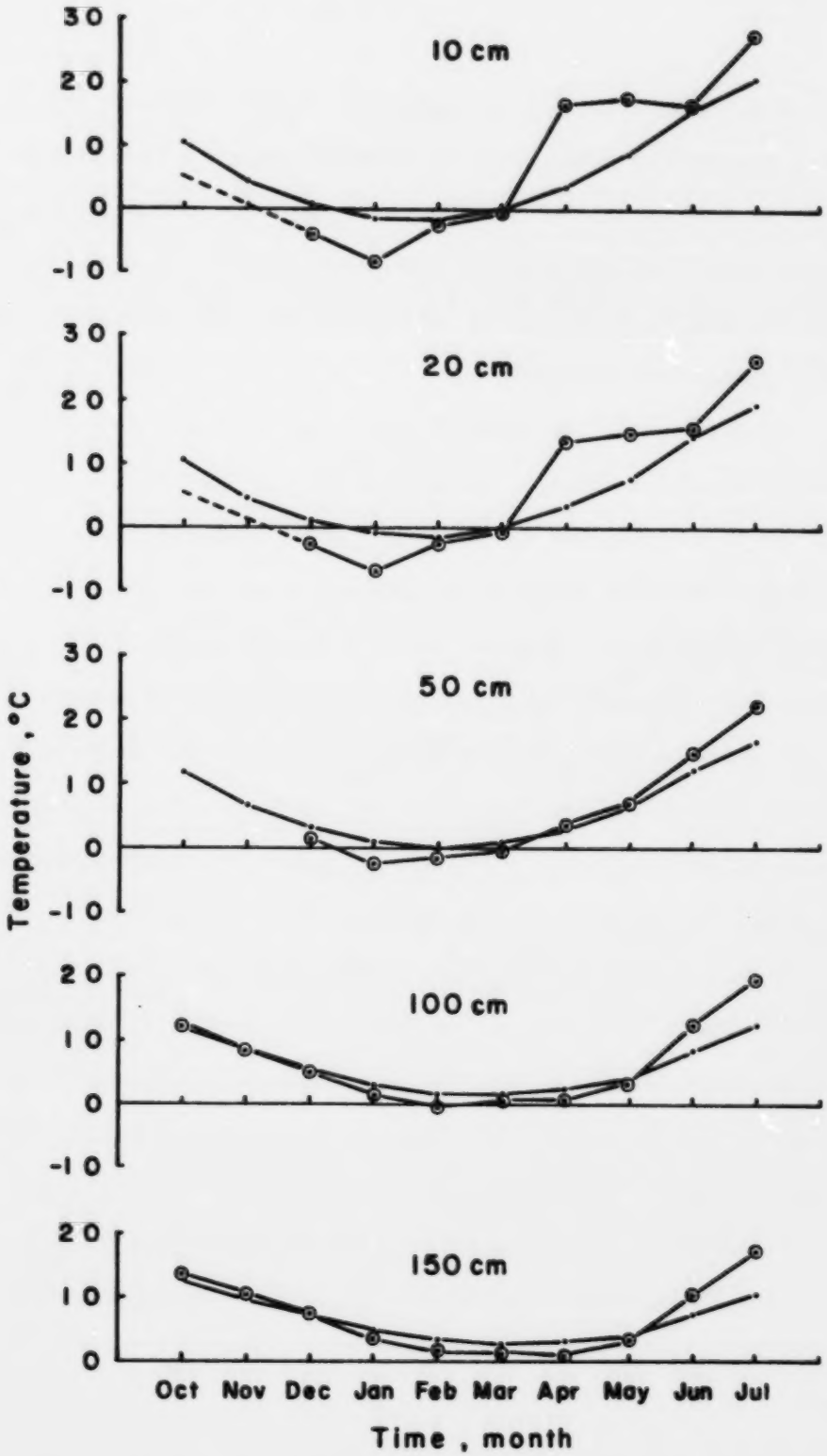

Fig. 5 - Experimental monthly soil temperature (o) and statistical approximation based on Ouellet's (5) regression analysis.

One observation that is consistent at all depths in Fig. 5 is the fact that the Ouellet model seems to underestimate the TS amplitude. Although agreement is good in general, in all cases the experimental minima and maxima are larger than those predicted by the model. This is consistent with observations made by Hayhoe et al. (4) when comparing experimental data to Ouellet's statistical approach.

Figure 6 shows the depth of the frozen boundary as a function of time, as given by Stephan's equation (described earlier) assuming a constant surface temperature of - 4.6°C, and as determined experimentally using thermocouples. Discrepancies can be as large as to show a 30 day difference for the frozen front position at 60 cm. Reasons for this difference are as follows. Firstly, the Stephan formula makes no provision for the insulating effect of snow cover. Hence, the above equation might be better suited for the study of frost penetration in road engineering and design problems. Secondly, other assumptions used to derive Stephan's formula (7) might not apply to our case, and hence account for the differences observed.

From the experimental curve in Fig. 6 it can be seen that the ground froze to a depth of at least 100 cm. According to Fig. 3, frost penetration reached the 122 cm depth in late February. This is fairly deep, but should be expected since the surface was free of snow for a long period of time during the winter months. Hayhoe et al. (4) report a frost line as low as 110 cm in a snow cleared plot. Depending on the size of the snow cleared plot it is possible that lateral heat transfer from the snow covered surrounding area might have affected the advance of the frozen boundary.

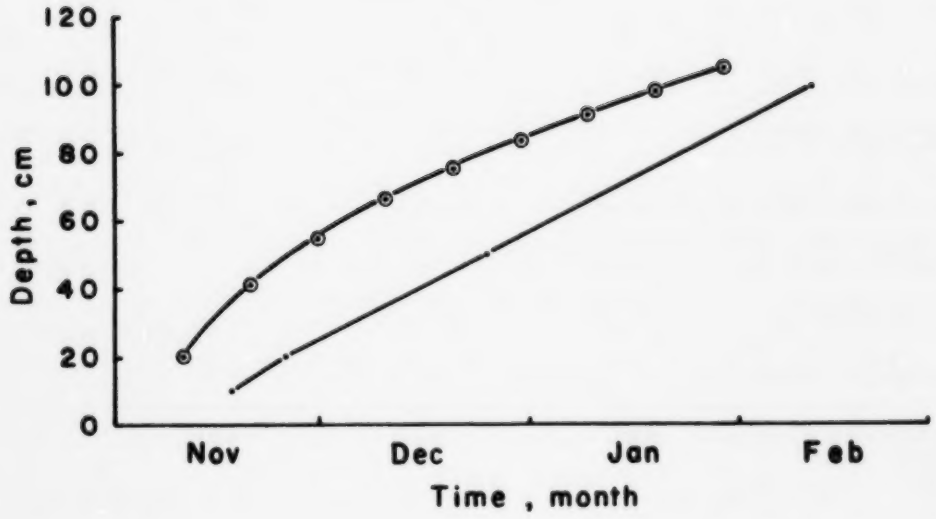

Fig. 6 - Experimental (·) and theoretical (-) advance of the frozen front at the tailings dam. The theoretical estimate is obtained from Stephan's expression, assuming a constant surface temperature of -4.6°C.

SUGGESTIONS FOR IMPROVEMENT AND CONCLUSIONS

In view of the comparison made between Ouellet's model and experimental data gathered at the tailings dam, one may conclude that the thermal properties of the soil tested here closely resemble those of typical Canadian soils. One of the major differences between the soils used to develop Ouellet's model and the tailings material is the consistency of the top layer. One might also expect tailings material to be more porous than ordinary soil. These differences seem to account for most of the discrepancies between Ouellet's model and the experimental results shown in Fig. 5.

In instances where it is not possible to monitor soil temperatures directly, some methods can be used that approximate TS profiles fairly well. The Ouellet method was found to be easy to implement and to agree fairly well with experimental results. It might be desirable to test other TS estimation models, such as the one described by Hayhoe et al. (4). This model was reported to perform quite well, given all the necessary meteorological information and soil properties are measured. The implementation of this method, however, requires relatively sophisticated computer facilities.

The depth of the frozen front as measured at the tailings dam was greater than what would be normally expected. The deeper advance can be accounted for mainly by the lack of snow cover throughout most of the winter. At first it was thought that lateral transfer through the dam might be responsible for the greater depth attained by the frozen boundary. Although this might be a factor, close examination of site geometry and comparison with Ouellet's model show that such heat transfer would not affect the frozen boundary greatly.

It would be desirable to monitor the advance and recession of the frozen front more closely. For this reason thermocouples could be placed at

10 cm intervals for the first 150 cm. This could be very helpful when monitoring frozen boundaries for the purpose of water drainage study in springtime. Other methods exist for locating frozen layers. Hayhoe et al. (4) have used the so called frost-tubes. These tubes are inserted at various depths in a configuration that allow them to be easily read. These tubes contain fluorescein saturated sand which changes colour on freezing. Time-domain reflectometry could also be used for determining soil freezing and soil moisture content.

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